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The FERMI free electron laser soft x-ray user facility

Enrico Allaria

Outline

- ✓ FERMI Free Electron Lasers
  - Layout and performances
  - FEL-1 results
  - FEL-2 results

- ✓ Control of the FEL properties
  - Bandwidth
  - Pump&probe possibilities

- ✓ FERMI experience at 13 nm

- ✓ Conclusions

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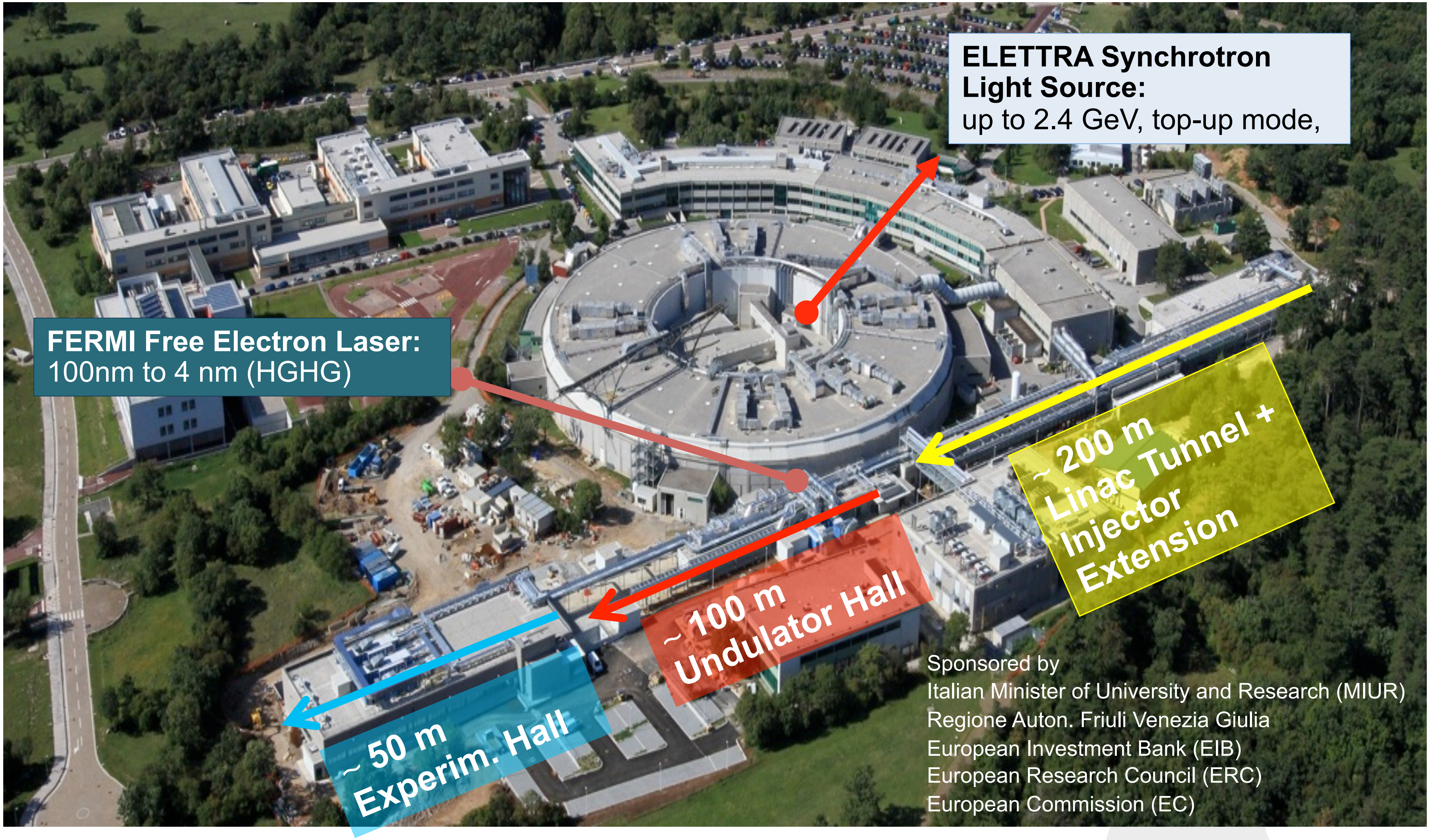
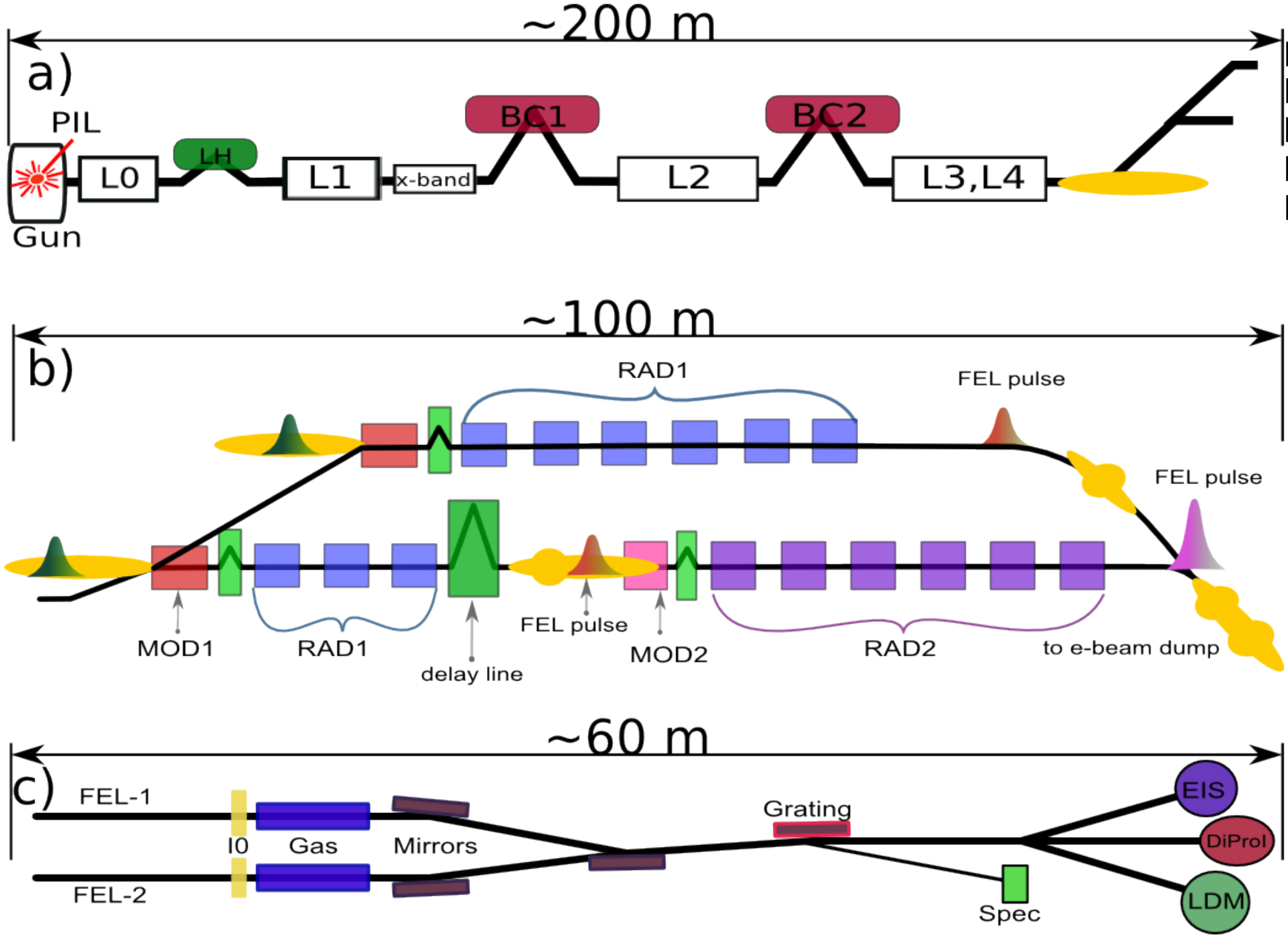


FERMI layout



Linear accelerator:
Rep rate 50Hz
Beam charge 700pC
Beam energy up to 1.5GeV
Peak current ~800A.

The **two undulator** lines use APPLE-II undulators. Both FELs are seeded by an UV laser.

FEL pulses are **analyzed** and **delivered** to the three **experimental stations**.

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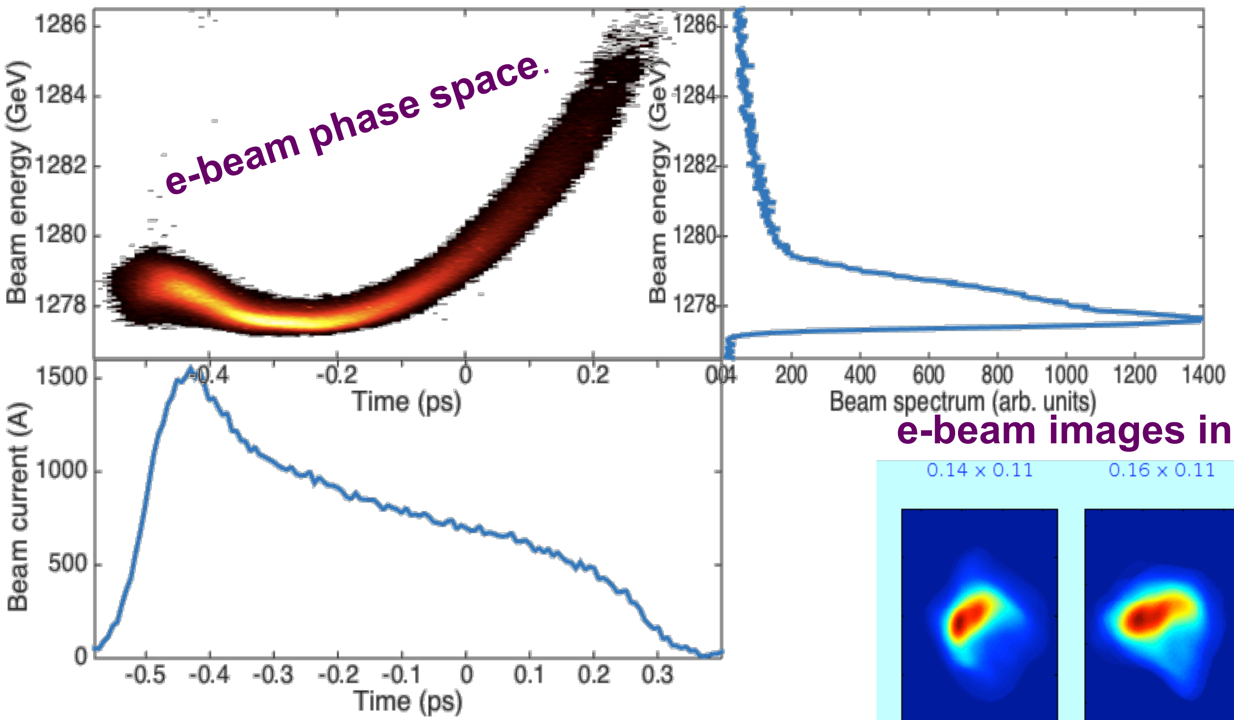
FERMI electron beam

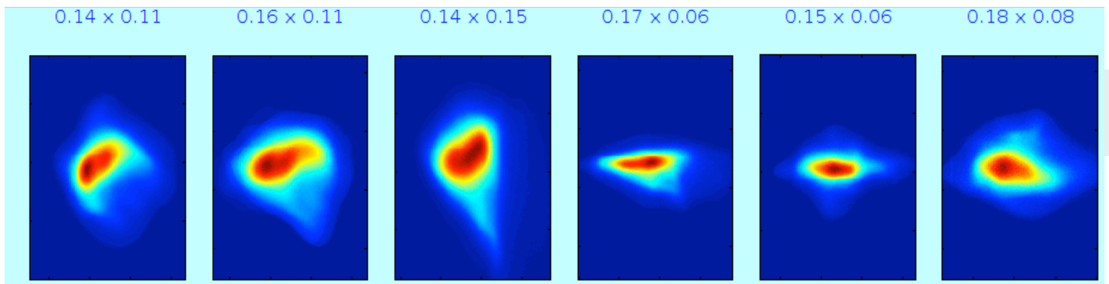
- Current **spikes** are **not suitable** for seeded FELs.
- **Low energy spread** and **flat phase space** are required for seeding.
- Electron beam **optimization** is **different** than for a **SASE** FEL.
- Moderate compression is used.



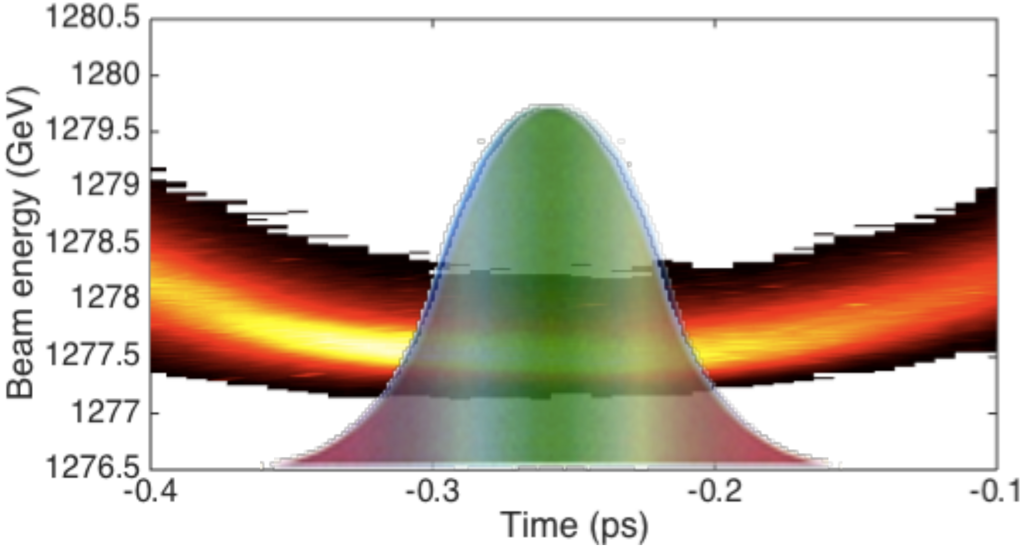
Electron beam parameters

Charge	700	pC
Peak current	~800	A
Energy	1 – 1.5	GeV
Energy spread	~150	keV
Energy chirp	~3	MeV
Emittance	1	mm mrad
Size (rms)	~100	μm

e-beam images in undulators.



Seeded electron beam



Head and **tail** parts of the beam can **deteriorate** FEL properties.

Seed laser pulse is **shorter** than the electron beam.
This allow to properly select the **best** part of the **electron** beam to participate to the **FEL process**.

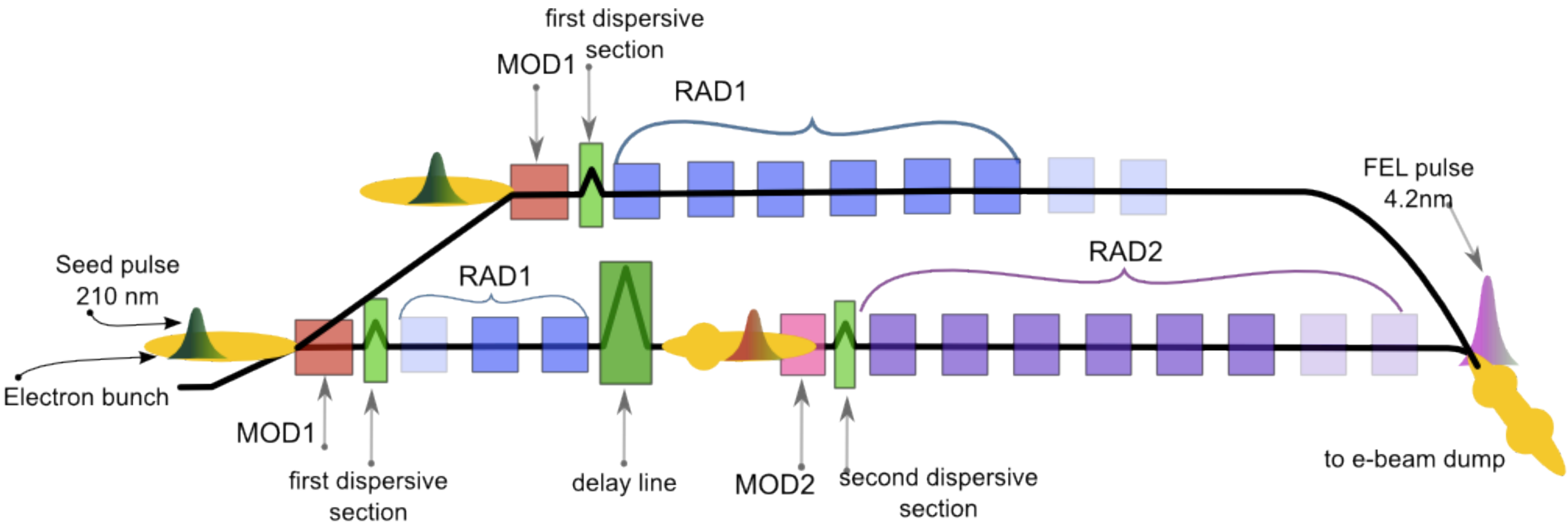
Because the final radiator is short the **unseeded part** does **not produce** any significant **radiation**.

But **electron beam** is **not uniform,** FEL properties may slightly depend on seed timing.

Typical seed **laser** is **~100fs** (FWHM) long and **few tens** of μ**J** are required to **optimize** the **FEL** and produce about **1GW** of peak power (~ 100μJ around 20nm).

FERMI FELs: FEL-1 & FEL-2

FEL-1, based on a **single stage high gain harmonic generation** initialized by a **UV laser**, covers the range from **100 nm** down to **20nm**.



FEL-2, covers the wavelength range from **20 nm** to **~4 nm** starting from a **seed laser** in the **UV**, with **a double cascade** of **harmonic generation**. It has a magnetic electron delay line to improve the FEL performance by using the **fresh bunch** technique.

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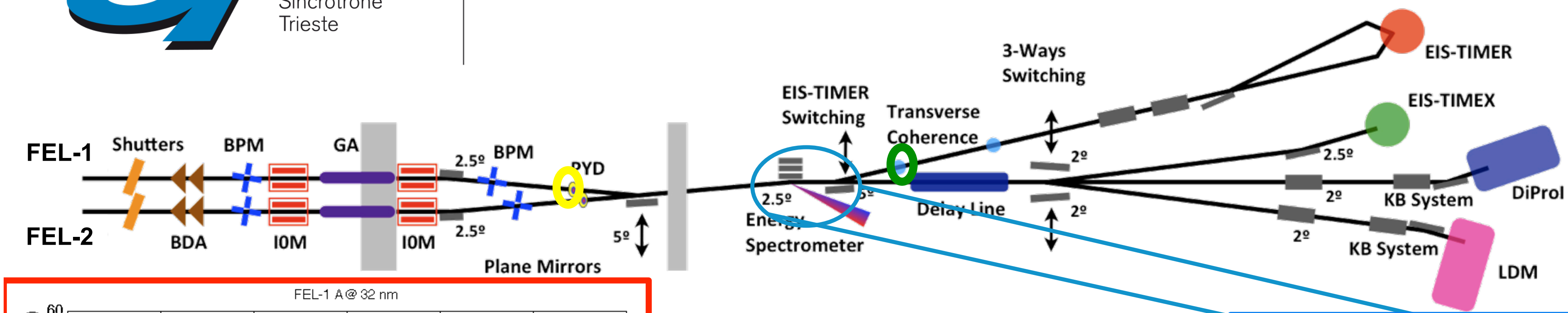
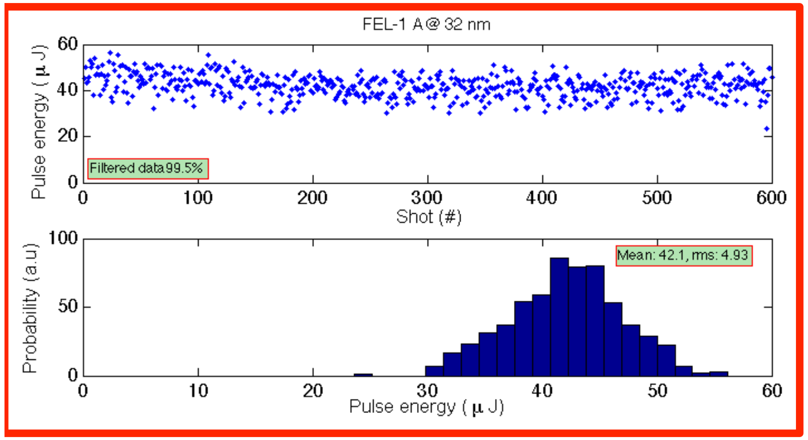
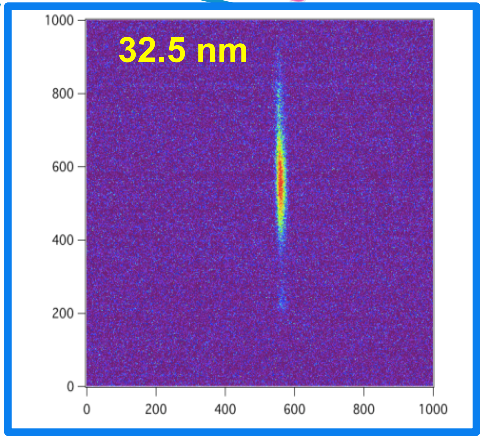
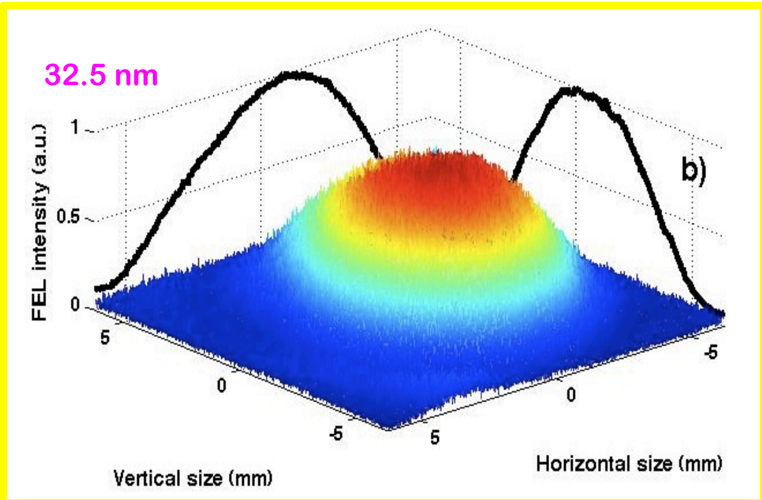
Photon diagnostic and transport systems

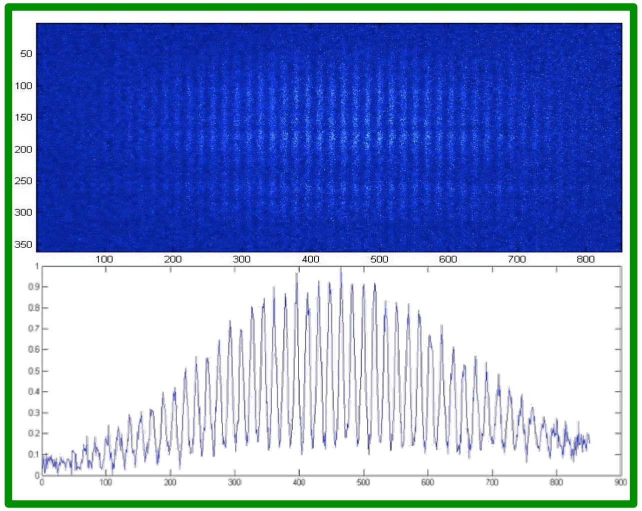




- Online FEL intensity monitors (I0),
- Gas attenuating cell (GA),
- YAG screen monitors,
- Photon beam position monitors (BPM),
- Calibrated photodiodes.



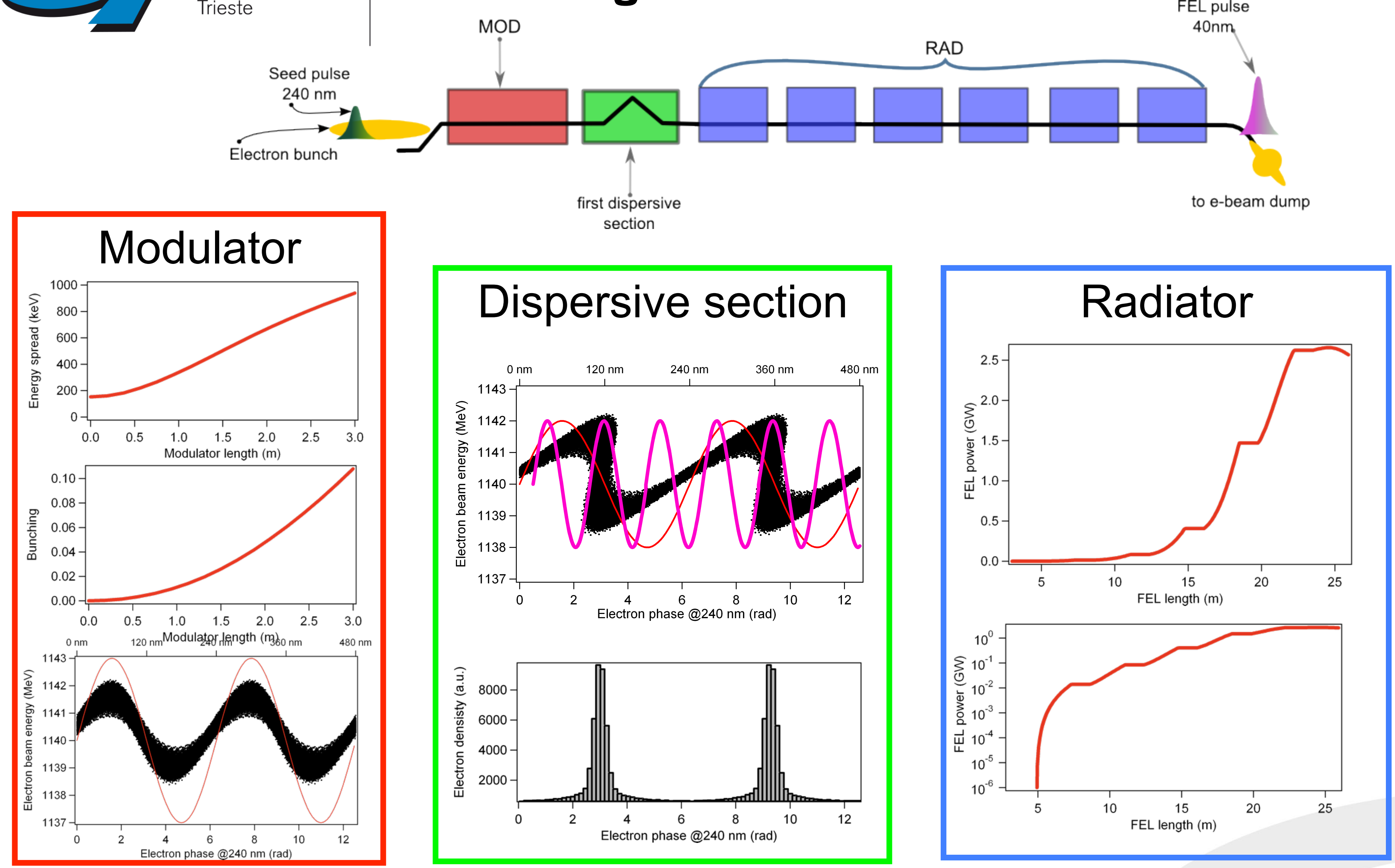




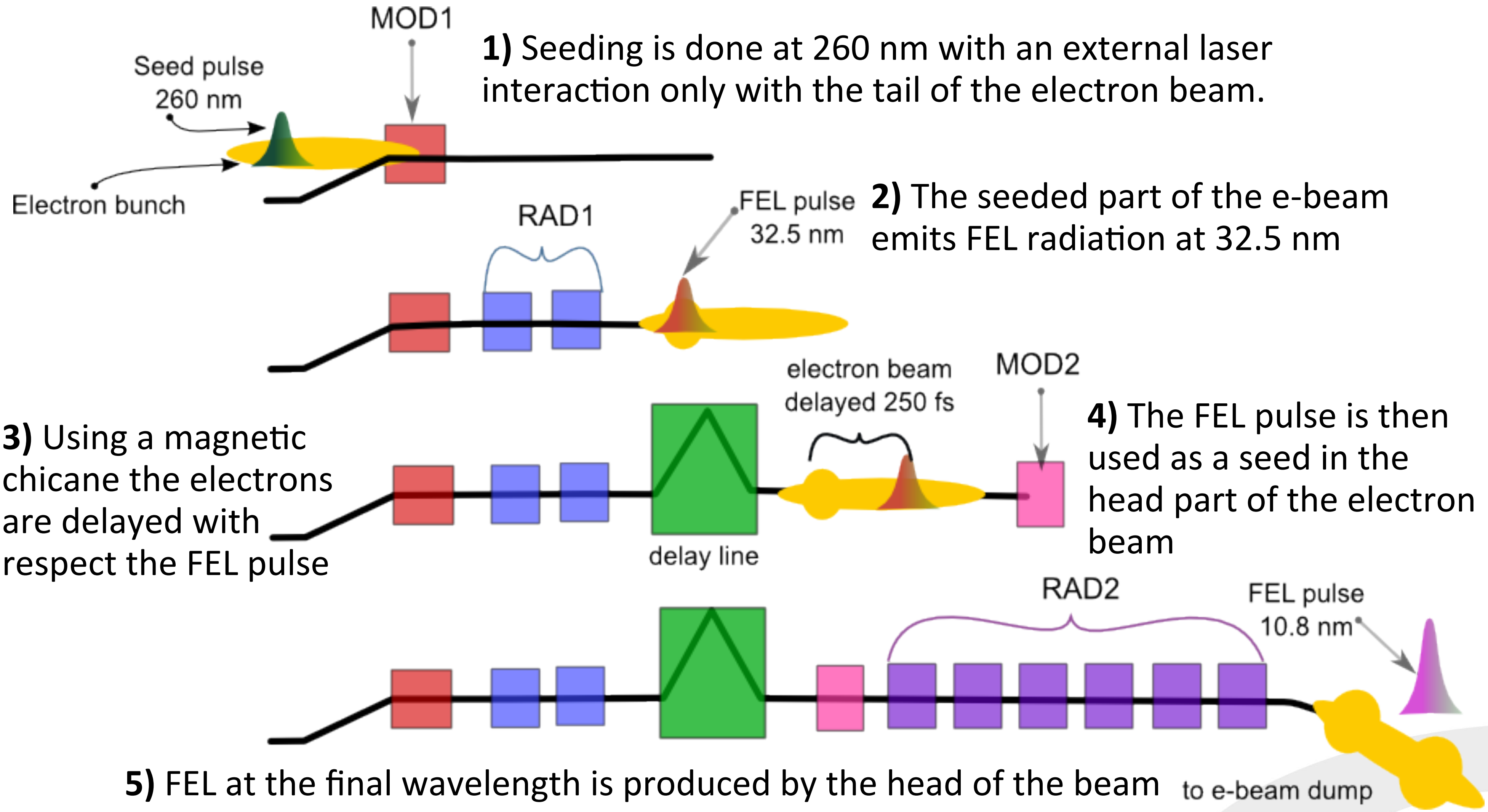
FEL spectrometer:

- Online (non invasive)
- Shot-to-Shot
- ~97% of FEL → beamlines
- 1% of FEL → YAG + CCD
- Res.power ~15000@32.5nm

FEL-1: High Gain Harmonic Generation



FEL-2: fresh bunch double cascade



1) Seeding is done at 260 nm with an external laser interaction only with the tail of the electron beam.

2) The seeded part of the e-beam emits FEL radiation at 32.5 nm

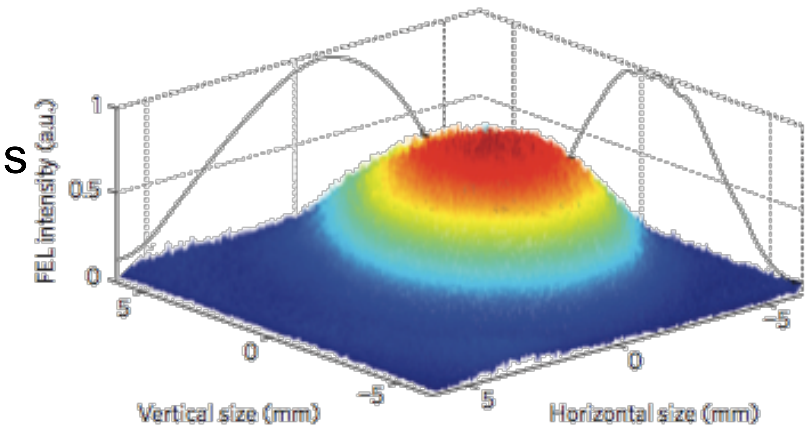
3) Using a magnetic chicane the electrons are delayed with respect the FEL pulse

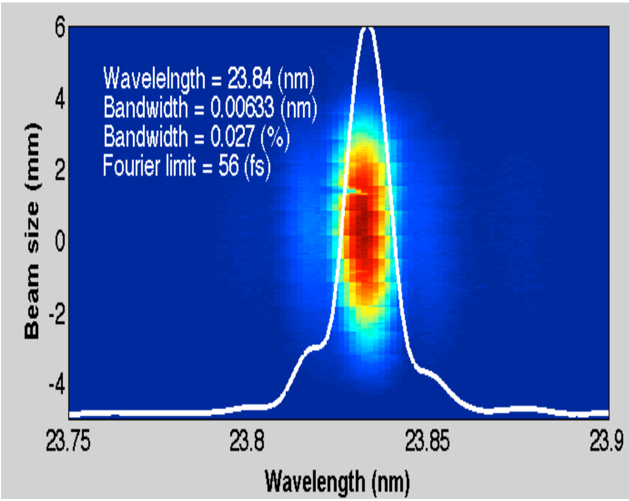
4) The FEL pulse is then used as a seed in the head part of the electron beam

5) FEL at the final wavelength is produced by the head of the beam

FEL-1: results

Similarly to other FELs the **transverse coherence** is good and emission is contained in a **TEM$_{00}$** mode.

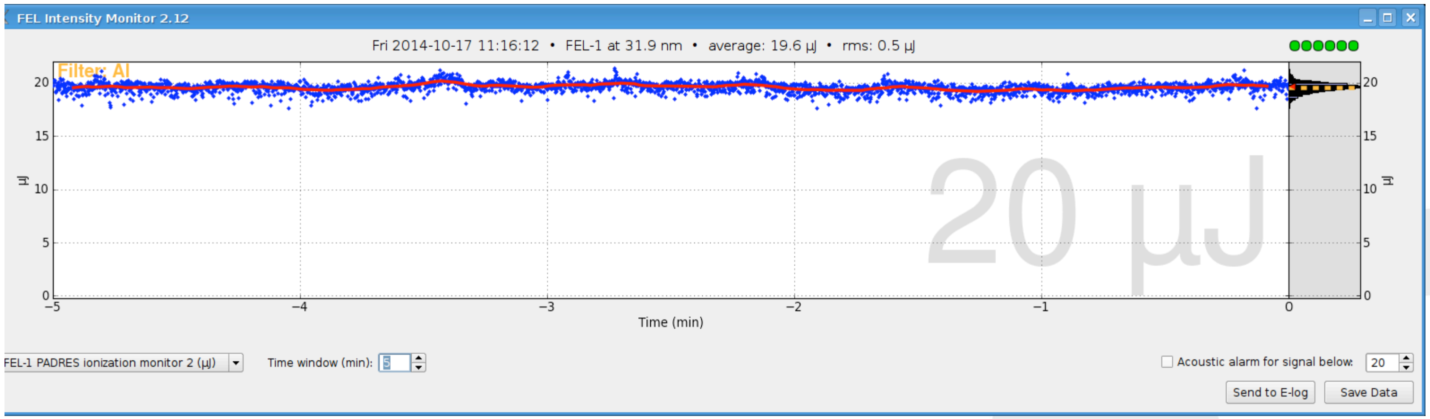




Typical measured **relative bandwidth** is few **10^{-4}** suggesting a **high degree** of **longitudinal coherence** and FEL **pulses** very close to the **Fourier limit**.

FEL power fluctuations are the results of the **jitter** in the **electron beam** and **seed** parameters.

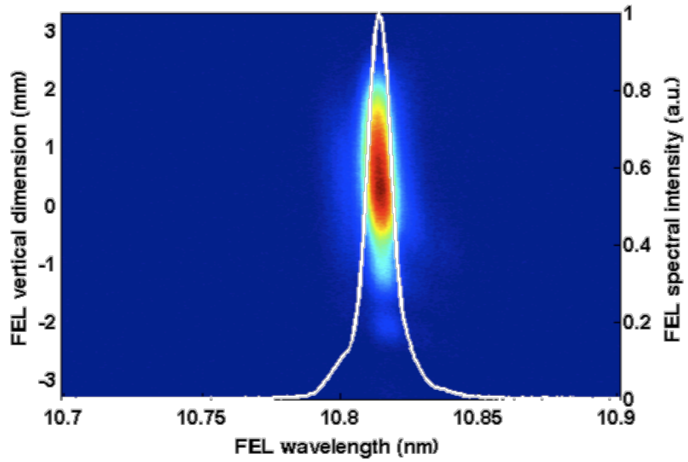
In **stable conditions** power **fluctuations** can be kept to the **few %** level.

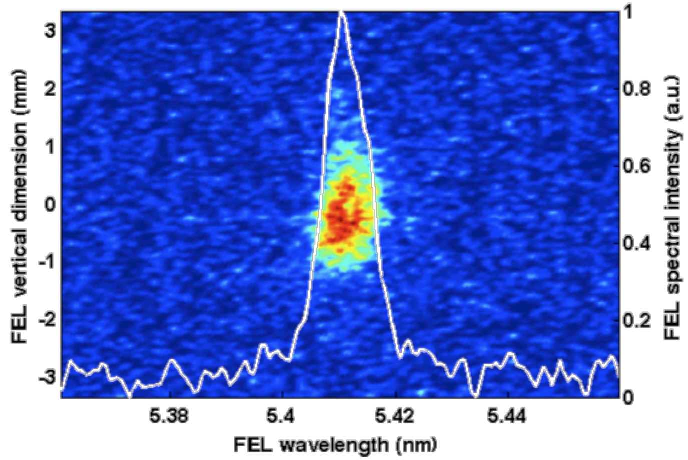


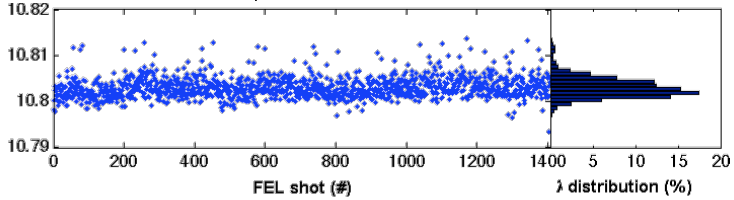
FEL-2 results

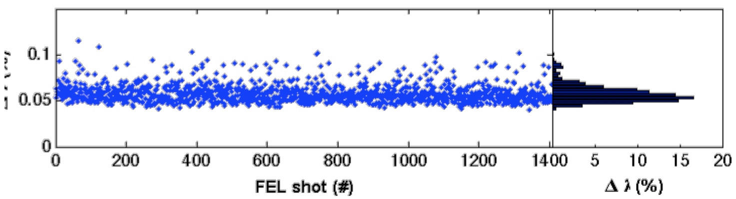
FEL-2 commissioning has been recently **concluded** and several **tens of μJ** have been **obtained** in the expected tuning range. Preliminary user **experiments** already **started**.

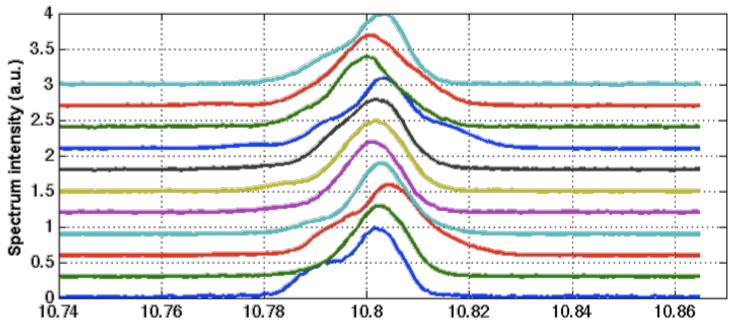
As for FEL-1, **FEL-2 spectra** are very **narrow**, clean and stable.











Typical numbers for FEL around **10 nm** is a wavelength stability of **$2*10^{-4}$** with an average **relative** FEL **bandwidth** of **$6*10^{-4}$** (sigma).

Pulse length has been measured to be in the range 40 – 80 fs.

FEL-1 at 12 nm

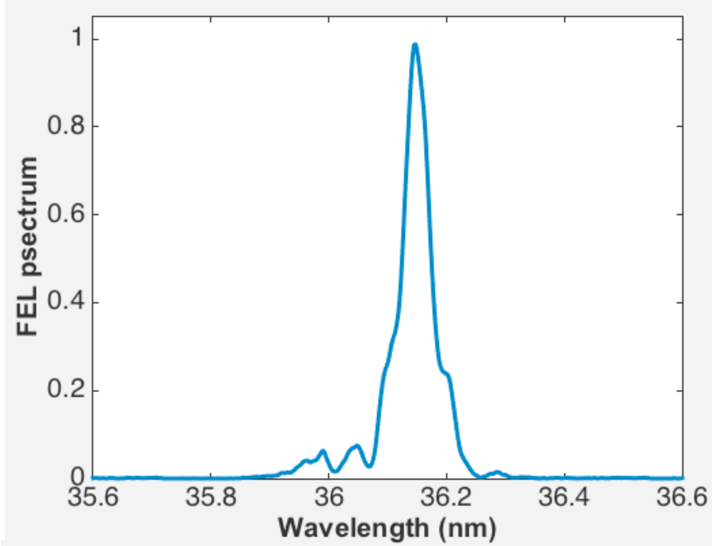
With **single stage** the **harmonic conversion** from the UV laser can be done **efficiently** down to ~ **20 nm** (H = 13).

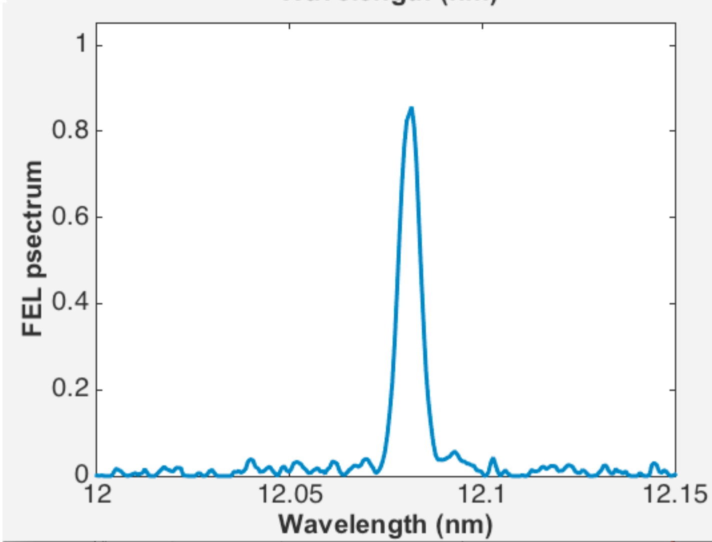
At **shorter wavelength** the **bunching** necessary **to start** the coherent emission would **require** a **strong seed** that compromises the FEL amplification.

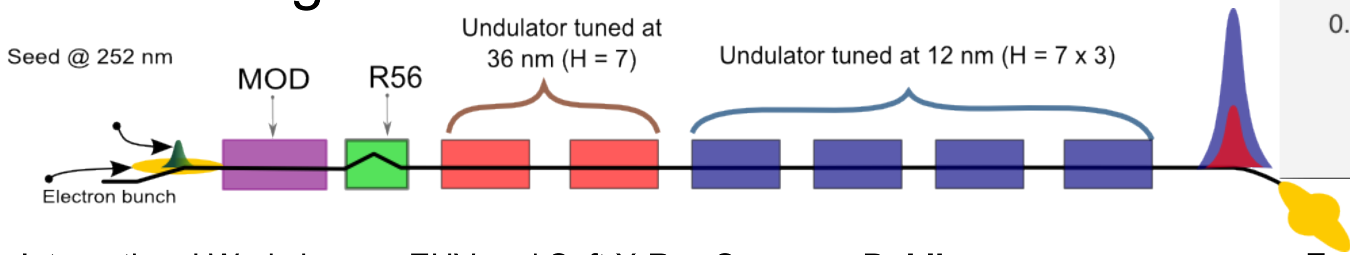
For final **wavelengths** in the **10 nm range** a scheme much **simpler** than the double stage cascade of FEL-2 **can be implemented**.

A low harmonics is slightly amplified before doing the final harmonic conversion.

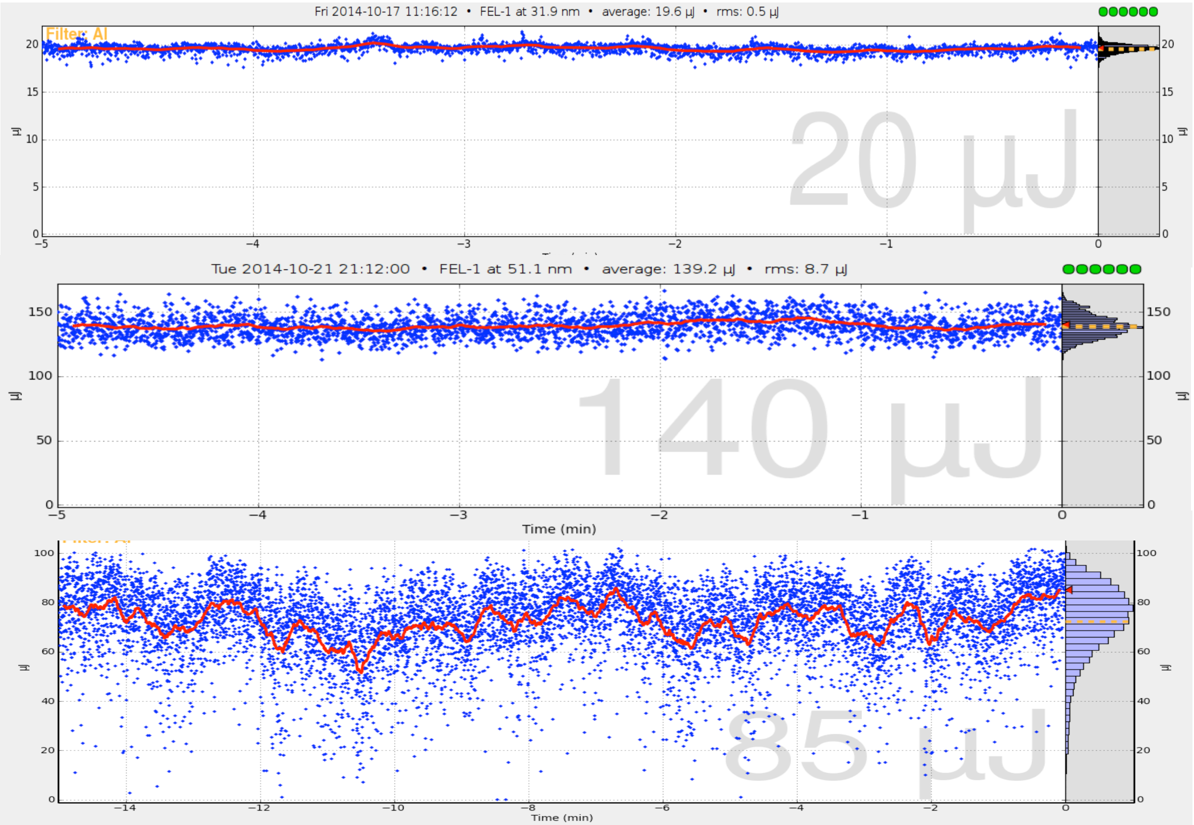
The scheme has been efficiently used at FERMI to generate 12 nm from FEL-1.







FEL stability



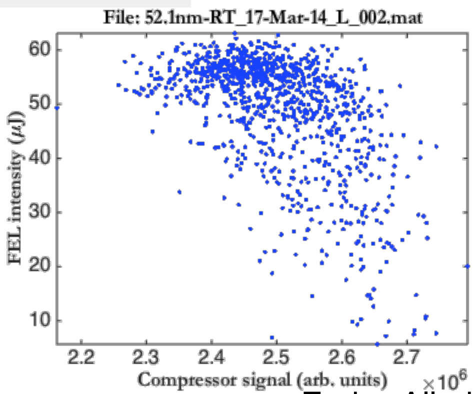
The **few %** rms power **fluctuation** has been shown to be **possible** but is **not always** achieved.

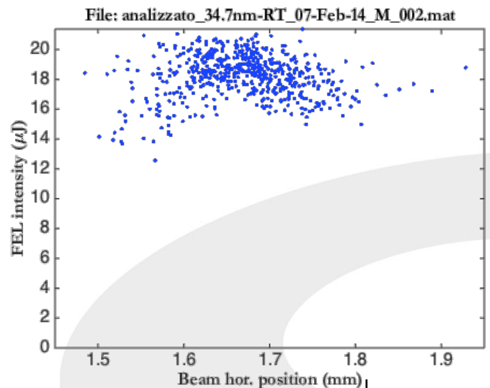
A more **typical** value for FEL power **fluctuations** is a value in the range **5 – 10%.**

But even **small problems** in one of the many **critical systems** can immediately introduce **slow drifts** and **increase** the power fluctuations.

Correlation between **FEL power** and **electron beam** and **machine parameters** can help in **recognizing** the critical **systems**.

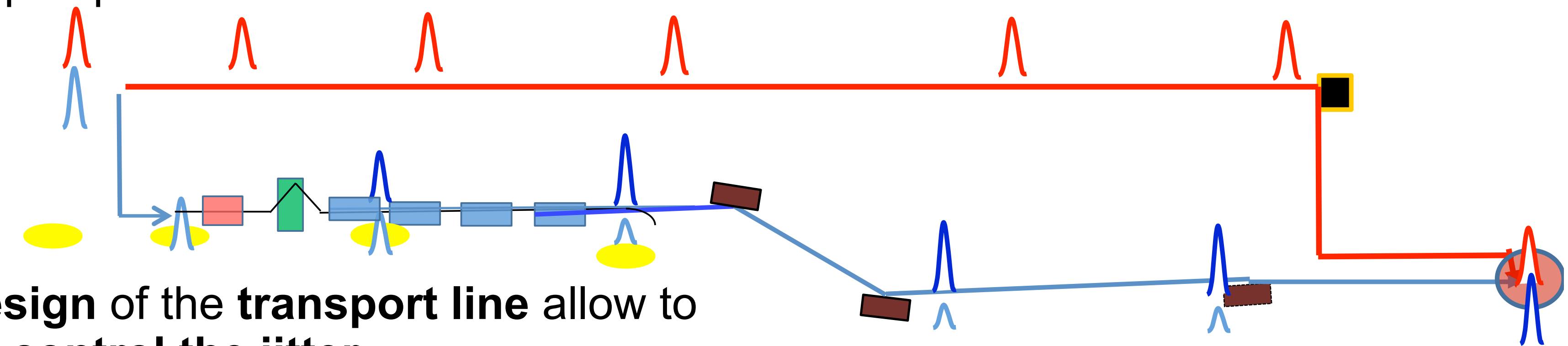
Feedbacks can help in reduce their impact.



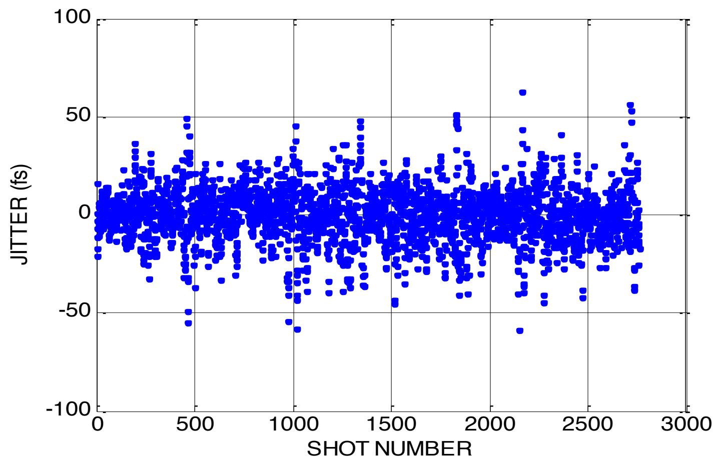


FEL timing control: pump&probe

- **Pump and probe** experiments can be done with **an external laser** used in combination **with the FEL**.
- **FERMI** profits of the fact that the **FEL is initiated** by the seed **laser**.
- **Part** of the **seed** can be **used** as a **pump reducing** the **jitter** between the FEL and the pump laser.



A proper **design** of the **transport line** allow to **keep** under **control the jitter**.



An **experiment** based on the FEL induced reflectivity changes in a Si3N4 allowed to **measure** the **jitter** that is below **10 fs**.

Optical beam transport to a remote location for low jitter pump-probe experiments with a free electron laser

Phys. Rev. ST Accel. Beams

P. Cinquegrana, S. Cleva, A. Demidovich, G. Gaio, R. Ivanov, G. Kurdi, I. Nikolov, P. Sigalotti, and M. B. Danailov

Accepted 19 March 2014

FEL pulses control: two pulses

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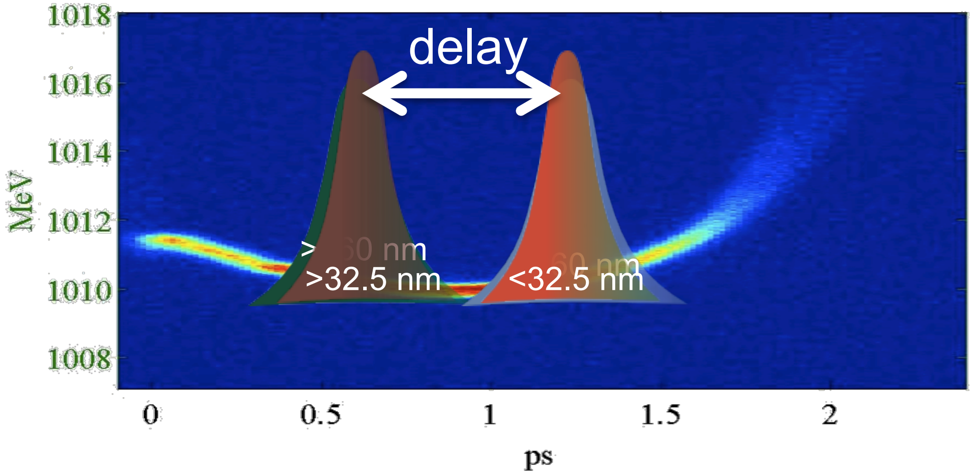
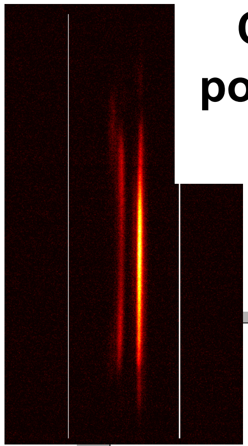
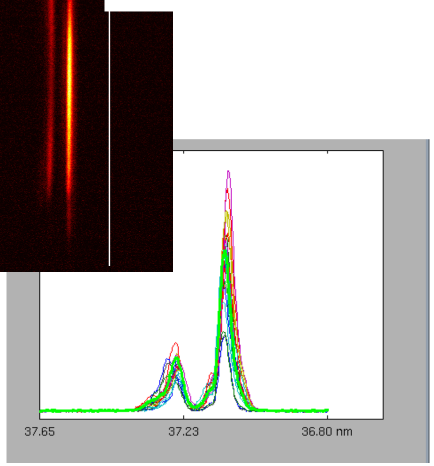
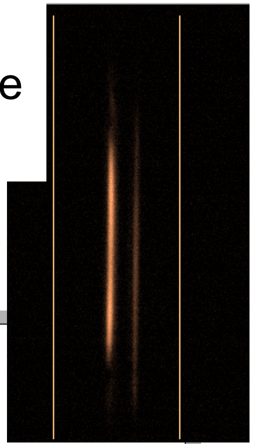
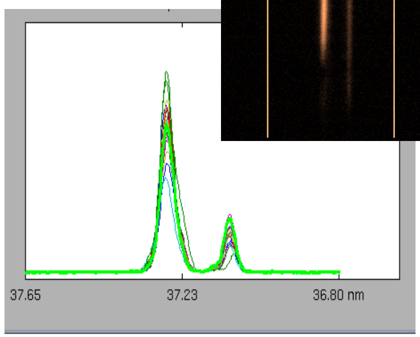


A **new** option for **pump and probe** experiments is based on the **double FEL pulse**.

Two seed pulses can be placed at **different timing** position on the beam and with slightly **different wavelength**.

Changes of the relative **power** and **timing** distance pulses **can be done**

The scheme demonstrated very **good wavelength** and **power stability**.

The scheme has been used for a **proof of principle experiment** done at the **DiProI** beamline.

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ARTICLE

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Two-colour pump-probe experiments with a twin-pulse-seed extreme ultraviolet free-electron laser

E. Allaria[1], F. Bencivenga[1], R. Borghes[1], F. Capotondi[1], D. Castronovo[1], P. Charalambous[2], P. Cinquegrana[1],

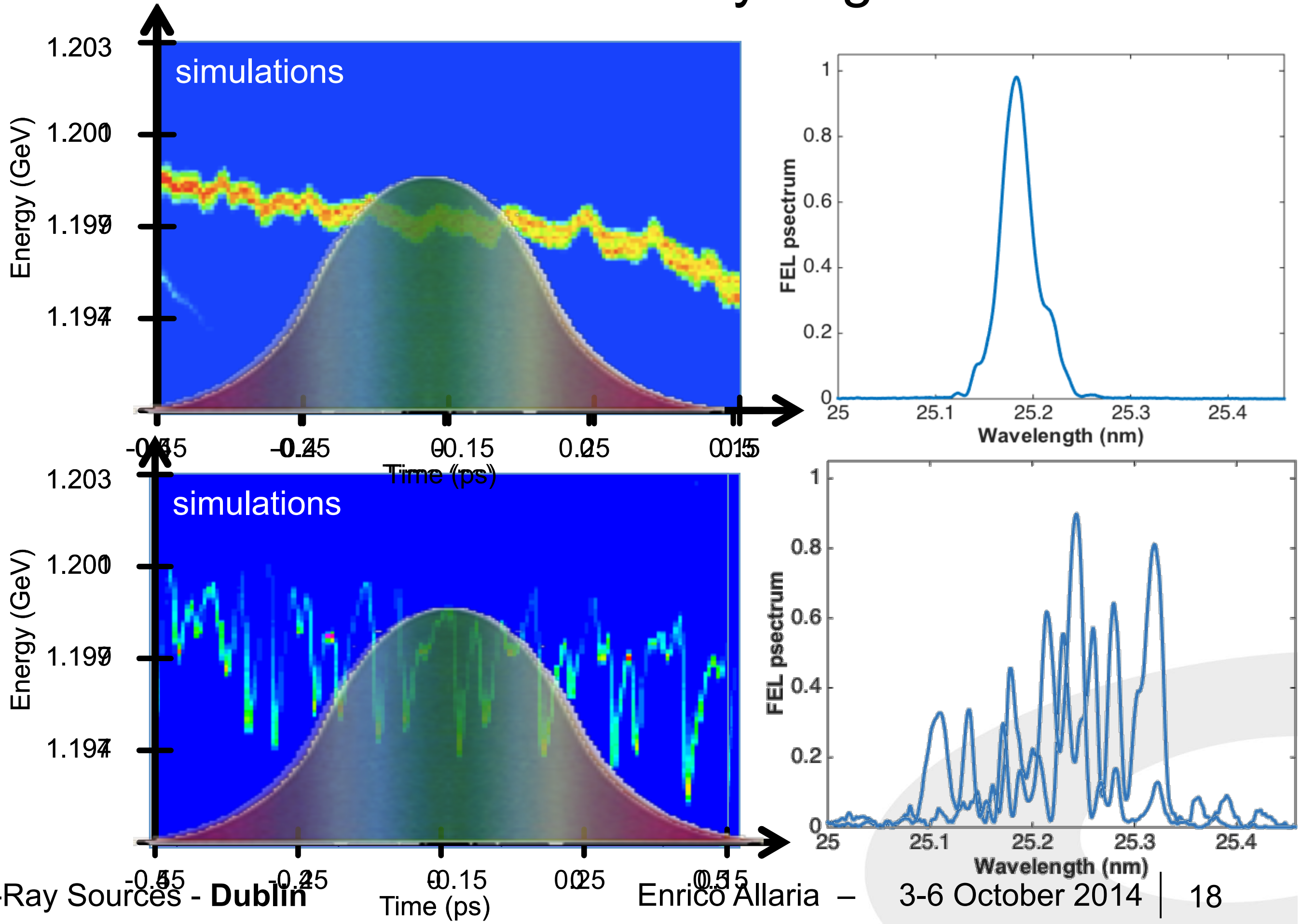
NATURE COMMUNICATIONS | 4:2476 | DOI: 10.1038/ncomms3476 | www.nature.com/naturecommunications

FEL spectra degradation

- The **high** degree of **longitudinal coherence** relies on the well **controlled** electron **phase space**.
- **Instabilities** can develop in the **accelerator** that **deteriorate** the **phase space**.
- A suitable **control** of the **instabilities** is necessary to get the **Fourier limited pulses**.

In case of interest the **phenomenon** can be **exploited** to **reduce** the **coherence** of seeded FEL pulses.

FEL spectra would be different at each pulse.



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Conclusions

- ✓ FERMI is providing **highly coherent** photon pulses in the **EUV – soft x-ray** spectral range.
- ✓ Spectral properties benefit from the external seeding allowing to produce FEL pulses close to the Fourier limit.
- ✓ Seeding has shown to improve also FEL energy stability.
  - HGHG FEL energy stability at the level of few % is demonstrated, but generally stability remains critically dependent on the stability of other subsystems (beam energy, electron orbit, seed laser ...).
- ✓ Operation of single stage HGHG at 13 nm has been demonstrated.

FERMI experience for EUV FELs

Based on the FERMI experience we can define a possible parameter list suitable for a FERMI-like EUV FEL.

- The **HGHG** could be a possibility for a powerful EUV FEL with sub-ps pulses with several tens of μJ per pulse.
- Both electron beam and seed laser requirements are reasonable.
- Problems could appear in case of very high repetition rates.

Electron beam		
Energy	1.2 – 1.5	GeV
Charge	~500	pC
Energy spread	100 – 150	keV
Emittance	1 – 1.5	mm mrad
Peak current	500 – 700	A
Size	100	μm

Seed laser		
Wavelength	210 – 240	nm
Seed pulse length	100 – 200	fs
Energy per pulse	20 – 50	μJ

Undulator		
Period	50	mm
Polarization	circular	
Length	15	m

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Thank you!

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